Search for New Physics in the Exclusive $\gamma_{Delayed} + \not{E}_T$ Final State at CDF

Analysis Update

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Outline

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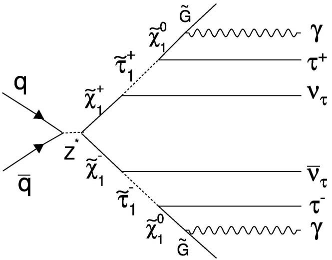
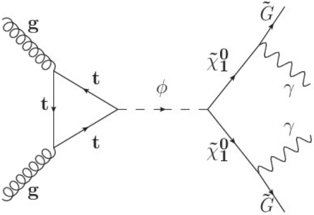
Introduction

- In Gauge Mediated SUSY Breaking (GMSB) models the Lightest SUSY Particle (LSP) is the Gravitino ($\tilde{G}$)
- Final states can decay to γ and $\tilde{G}$ ($\not{E}_T$)
- In Minimal models (usually we use SPS-8 for simplicity) searches have focused on the $\gamma\gamma + \not{E}_T$ (short lifetime) final state produced in association with other particles
- A small coupling (long lifetime) between the LSP and Next to LSP (NLSP) is favored in cosmological models and generally gives $\gamma_{Delayed} + \not{E}_T$



Both searches performed at CDF for minimal models, with most recent results in 2007 and 2010. Current limits now dominated by squark-gluino production at LHC.

References:
SPS-8: EPJ C25, 113 (2002)
Pheno: PRD 70, 114032 (2004)
CDF Searches: PRL 99, 121801 (2007)
& PRL 104, 011801 (2010)

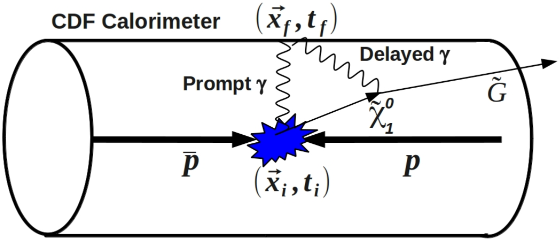


- Many GMSB models exist
- In the Light Neutralino and Gravitino (LNG) scenario, only the lightest Neutralino and Gravitino are accessible at colliders (others have large masses)
- New scalar production (Φ), like a Higgs, can lead to large cross sections for direct pair-production of $\tilde{\chi}_1^0$ and no other associated particles
- For long-lived $\tilde{\chi}_1^0$, we look for the exclusive $\gamma_{Delayed} + \not{E}_T$ final state (N.B. - No observations in exclusive $\gamma\gamma + \not{E}_T$ searches, which excludes short lifetime scenarios)

References: PRD 80, 115015 (2009), PLB 702, 377 (2011) & PRD 82, 052005 (2010)

More details about the Delayed Photon Signature

For a $\tilde{\chi}_1^0$ (NLSP) with a lifetime of a few nanoseconds, it can decay to a γ and a $\tilde{G}$ (LSP) within the detector.



Photons from such decays arrive at the calorimeter later than expected from prompt photons, giving the distinct *delayed* photon signature. Previously published CDF Results on this include both model-dependent ($\gamma_{Delayed} + jet + \not{E}_T$) and model-independent ($\gamma_{Delayed} + \not{E}_T$) studies. $\gamma_{Delayed} + jet + \not{E}_T$ now superseded by LHC, and $\gamma_{Delayed} + \not{E}_T$ is probably impossible at LHC with our energies.

References: Model-dependent: PRL 99, 121801 (2007) & PRD 78 032015 (2008)
Model-independent: PRD 88, 031103(R) (2013)

Backgrounds

Reminder of Backgrounds, Timing and Overall Search Strategy

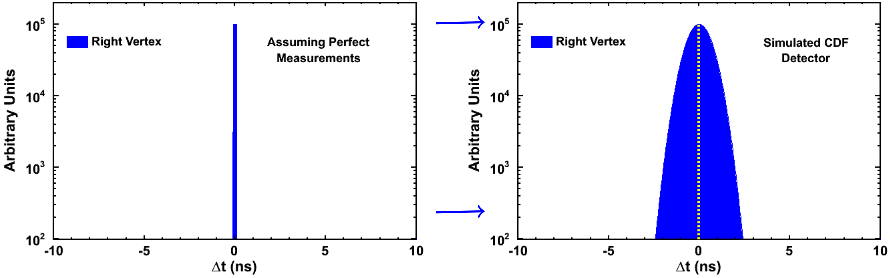
- The dominant sources of background for the exclusive $\gamma_{Delayed} + \not{E}_T$ final state are:
  1. Photons from Standard Model collisions
  2. Photons from cosmic ray sources

- Methods of separating delayed and prompt photons with timing:
  1. The Δt variable: take time of arrival (from EMTiming), subtract off time of collision (from COT) and expected time-of-flight (from CES and COT)

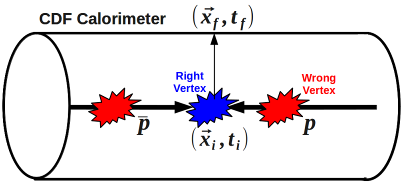
We construct the timing distribution of the background sources:

$$\Delta t = (t_{\mathrm{f}} - t_{\mathrm{i}}) - \frac{(|\vec{x}_{\mathrm{f}} - \vec{x}_{\mathrm{i}}|)}{c}$$

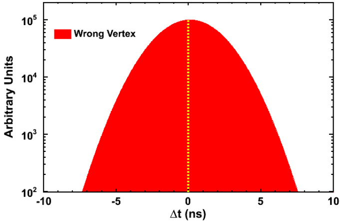
In a perfect detector Δt would be exactly zero. With real data we use the highest $\sum P_T$ vertex in every event and our detector has a resolution of 0.65 ns.



References: NIM A563, 543 (2006) & CDFNote 7928



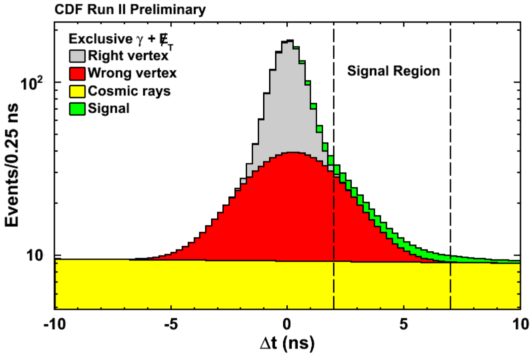
However, there are often multiple vertices in an event. Sometimes, the correct one may not be picked/reconstructed. We classify events as either having a "Right Vertex" or a "Wrong Vertex." The WV distribution has an RMS of ~ 2.0 ns, but the mean is not 0.



Reference: CDFNote 9924

Lastly, we account for cosmics as a flat-in-time distribution, resulting in our final background estimation shape* .

Any potential signal excess would appear as a decaying exponential (normalization and slope depend on the physics involved - more in references).



*Cosmics details in upcoming section

References: PRD 70, 114032 (2004), PLB 702, 377 (2011) & JHEP 09, 041 (2013)

The dominant backgrounds to the exclusive $\gamma_{Delayed} + \not\!\!E_T$ final state are:

Standard Model Collision Sources
$W \to e\nu \to \gamma_{\text{fake}} + \not\!\!E_T$
$\gamma + \text{jet} \to \gamma + \text{jet}_{\text{lost}} \to \gamma + \not\!\!E_{T\,\text{fake}}$
$W\gamma \to l\nu\gamma \to \gamma + l_{\text{lost}} + \not\!\!E_T$
$W \to \mu\nu \to \gamma_{\text{fake}} + \not\!\!E_T$
$W \to \tau\nu \to \gamma_{\text{fake}} + \not\!\!E_T$
$Z\gamma \to \nu\nu\gamma \to \gamma + \not\!\!E_T$
Non-Collision Sources
Cosmics
Beam Halo
Satellite Bunches

Table: Standard model and non-collision backgrounds for the exclusive $\gamma + \not\!\!E_T$ search.

References: CDFNotes 7960, 8409 & 9812

Cuts for the exclusive $\gamma_{Delayed} + \not{E}_T$ final state:

Quantity	Selection Cut
Trigger	`WNOTRACK`
Good Isolated Photon	$E_T > 45$ GeV (ID in backups)
$\not{E}_T(z=0)$	> 45 GeV
Good Space-time Vertex	Within $\lvert Z \rvert < 60$

In addition, the event is rejected if any of the following veto requirements "passed":

Veto	Requirement
Jet Cluster	$E_T > 15$ GeV
Track p_T	$p_T > 10$ GeV
Vertex Z	$\lvert Z \rvert > 60$ cm
Cosmics Rejection	Backups
Beam Halo Rejection	Backups

References: CDFNotes 9924 & 10773

Signal Region defined to be (2 ns $< \Delta t <$ 7 ns). Background distributions have known shapes, but their rates are estimated from data outside the signal region, where the:

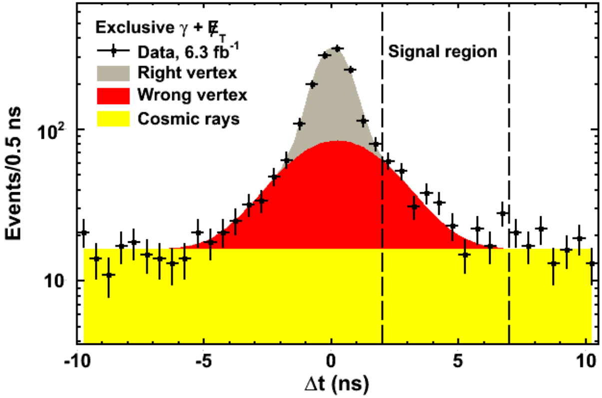
- "Right Vertex" $\rightarrow$ Mean $= 0 \pm 0.05$ ns, RMS $= 0.65 \pm 0.05$ ns
- "Wrong Vertex" $\rightarrow$ Mean = taken from a "No Vertex" sample, RMS $= 2.0 \pm 0.1$ ns
- "Cosmics" $\rightarrow$ Rate calculated using events within the (20 ns $< \Delta t <$ 80 ns) range

Perform combined binned log likelihood fit to predict expected events in the signal region

References: CDFNotes 9924 & 10787

Overview
Previous Results and Conclusions

This analysis was done with $6.3 fb^{-1}$ as a model-independent search and published in PRD-RC in 2013 (CDFNote 10789, PRD 88, 031103(R) (2013)).
Result: 286 ± 24 events expected in the signal region with 322 observed (and gives a *p-value* of 12%). No limits were set.



Full Run II Dataset Analysis

Analysis now being done with the full CDF Dataset with better timing calibrations and background estimation. This includes:

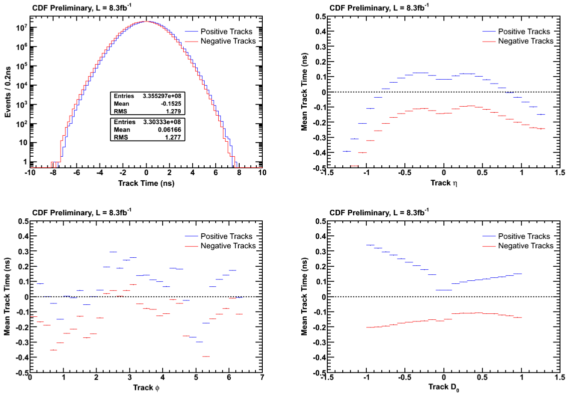
- Use the full CDF Dataset ($8.3 fb^{-1}$)*
- Calibrate tracks and EMTiming system in a more systematic way
- Change in cosmics background estimate
- Set limits on new physics processes

* This number is less than the usual data size of other analyses due to two reasons:

- Removed low luminosity runs due to lack of statistics for calibrations ($\sim 300 pb^{-1}$)
- First $400 pb^{-1}$ of CDF data had no EMTiming system installed

Reference: JHEP 09, 041 (2013)

Out-of-the-box track timing is not well centered and has large systematic variations out to 0.5 ns. Want to define the origin as the average collision time $\bar{t_0} = 0$ (CDFNote 10607) at $Z = 0$.
Note - trying to get rid of these variations by making them smaller (~ 15 ps) than the track resolution (which is < 250 ps).



Tracks used for this study come from *bhel*∗ stream events where only good tracks are required:

Quantity	Selection Cut
P_T	> 0.5 GeV†
$\lvert\eta_{\text{track}}\rvert$	≤ 1.4
$\lvert Z\rvert$	≤ 70 cm
$\lvert d_0\rvert$	≤ 1.0 cm
$T_0\sigma$	≥ 0.2 ns & ≤ 0.8 ns
COT Stereo(5)	≥ 2
COT Axial(5)	≥ 2

†Changed from 0.3 GeV

A well calibrated COT would have a mean of $t_0 = 0$ as a function of all track parameters: η, Φ, p_T, D_0 & $T_0\sigma$

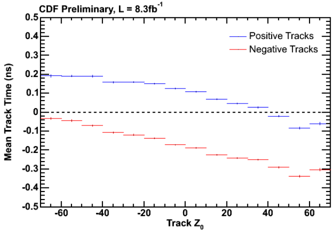
New Track Calibration Methods and Results

Old method described in CDFNote 10607. New and better method required because after those calibrations there were still systematic variations in some parameters at the 100 ps level. New procedure:

1. Coarse corrections by setting mean collision time to $t_0 = 0$ at $Z = 0$ run-by-run
2. 1-D corrections based on the mean time vs. p_T distribution to remove gross features
3. Correct for tracks being calibrated to outer part of detector instead of the inner part: Remove correlation between Φ and p_T (more details on next slides)
4. 1-D corrections based on all 5 parameters to remove more gross features
5. 2-D correction based on p_T and $T_0\sigma$

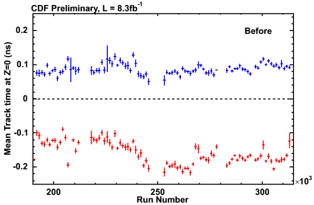
The latest status of the timing calibrations can be found on the analysis webpage:
http://www-cdf.fnal.gov/~vaikunth/internal/calibrations.shtml

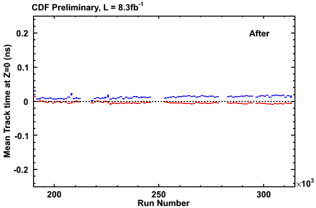
Because of the proton and anti-proton beam structure, t_0 is a function of Z:



- Consider tracks in good vertices
- Treat "Positive" and "Negative" tracks separately
- Determine offset run-by-run, separately for both

Perform linear fit from $[-40, 40]$ cm to get the offset as a correction for every run.

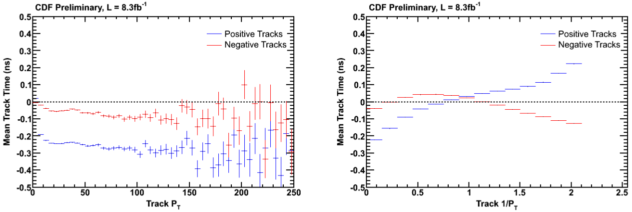




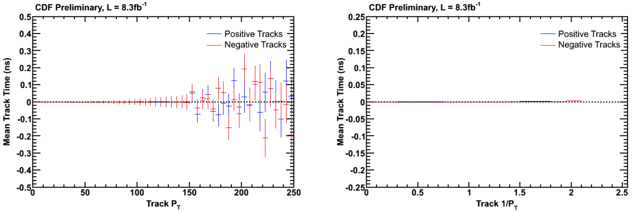
Note: "After" plot not completely flat because coarse corrections make tracks enter/leave vertexing sample considerably. This will get fixed during later steps.

Reference: CDFNote 9812

After the run-by-run corrections, we look at the mean time vs. p_T and $1/p_T$ (to study both high and low p_T values). Both have large variations.



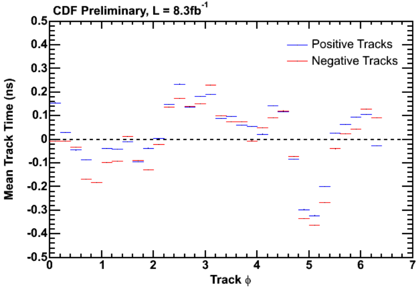
Since p_T is the most correlated variable with other parameters, we make 1-D corrections to it first. Perform two iterations of corrections → now essentially flat.



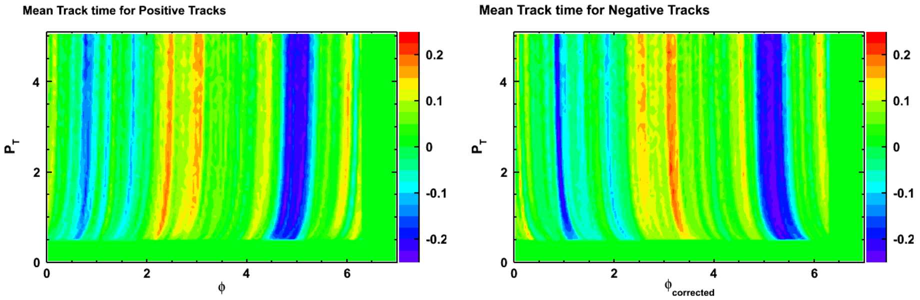
Next, deal with large variations that still remain in Φ.

These were not understood in the previous analysis, but averaged out using vertexing which selects over many different Φ.

Went back to understand this, both to better calibrate as well as get more tracks into vertexing.



The mean time is a function of Φ and of p_T separately, but we also found that Φ and p_T are correlated:



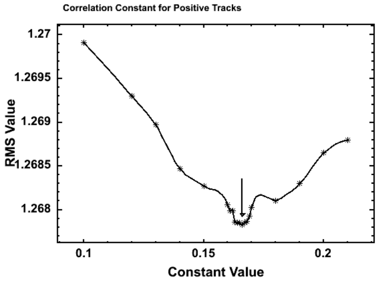
Appears that the tracking was calibrated so that mean time t_0 is centered at the outer part of the detector, not the inner part - or something similar:

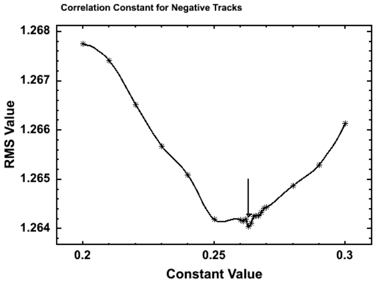
$$\bar{t_0} \propto \Phi + \frac{< constant >}{p_T} \tag{1}$$

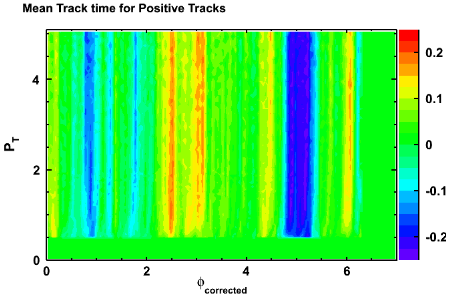
Transform from mean time as a function of (p_T vs. Φ) to (p_T vs. $\Phi_{corrected}$), where:

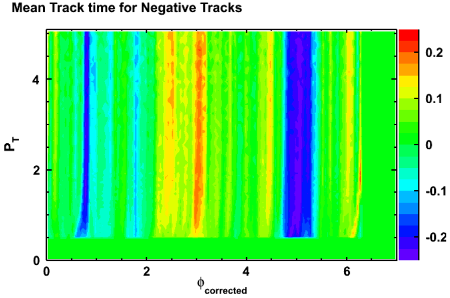
$$\Phi_{corrected} = \Phi + \frac{C}{p_T} \quad (2)$$

Minimize the RMS of the timing distribution as a function of C. Pick minimal value as our constant.



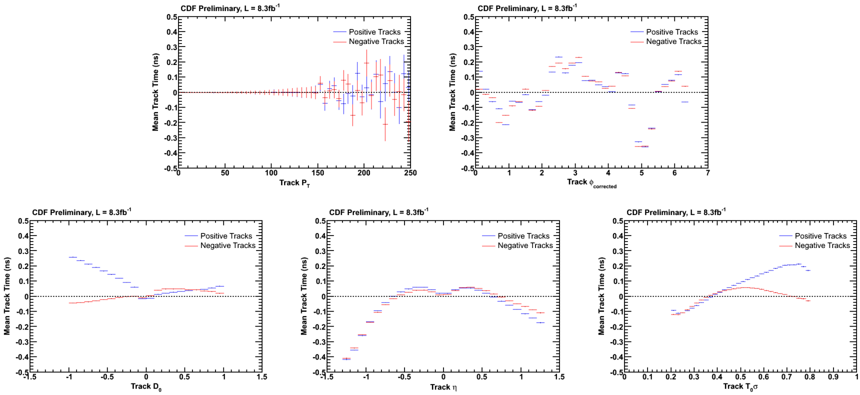






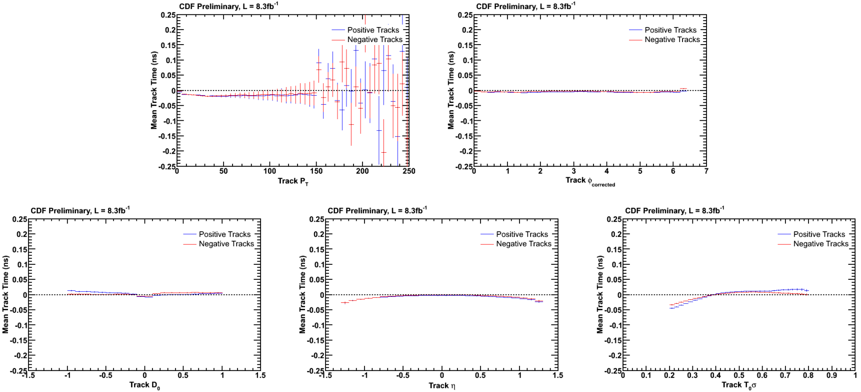
After this "adjustment," $\Phi_{corrected}$ now shows minimal correlation. Can now calibrate other parameters with 1-D corrections in parallel now that most egregious cases of p_T and ϕ have been handled individually.

At this point, the mean track time distribution has no variations in p_T and we are ready to apply 1-D corrections based on $\eta, \Phi_{corrected}, D_0$ & $T_0\sigma$



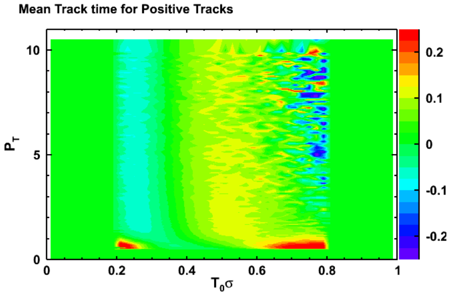
Variations are now at $\sim$ 0.35 ns.

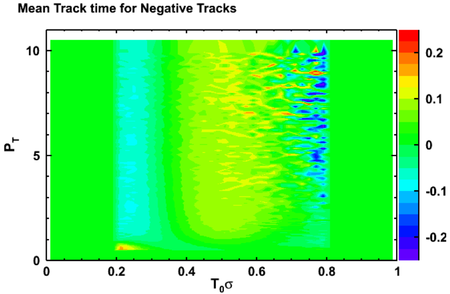
We also perform 2 iterations of these 1-D corrections in the other parameters, with the following results



There is still structure, which is due to correlations between variables. Need correlation corrections.

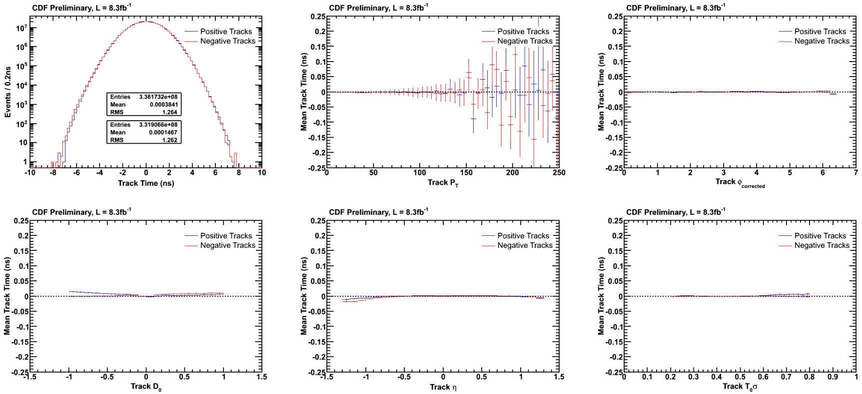
Largest correlation is between p_T and $T_0\sigma$:





We apply a 2-D correction based on this plot for positive and negative tracks separately. Variations at 0.25 ns.

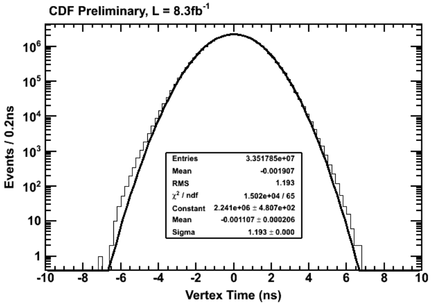
After all these corrections added in, the results for all parameters of interest are as follows:



Could keep doing this forever, but with everything below $\sim$ 15 ps we stop here since we will have multiple tracks per vertex which makes it average out.

Vertices

Vertices produced from these tracks are well-centered and very Gaussian for almost 6 decades in log scale.



In the $6.3 fb^{-1}$ analysis, there was a calibration needed to center the mean time for vertices run-by-run. This is no longer needed since tracks are now so well centered. Excellent check of the method.

Next steps: Full vertex validation for the calibrations will be done on an $e + \not\!\!E_T$ data sample and shown against the calibration parameters (work in progress).

Next Steps in Calibration using the $e + \not{E}_T$ sample:

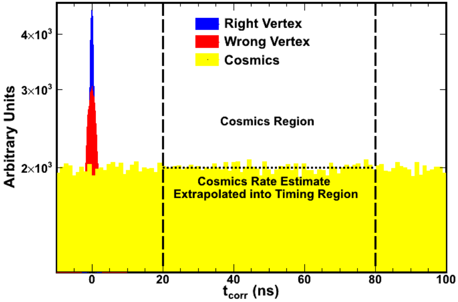
- Calibrate EMTiming (t_f part of Δt equation)
    - Begin with run-by-run offset corrections
    - Energy corrections
    - "Ring" corrections

When EMTiming corrections are done, we are ready to do the data analysis.

Reference: CDFNote 10607

New Background Estimate for Cosmics

Old background estimate assumed the cosmics distribution to be flat in time, and calculated by averaging cosmics events away from the signal region at $[20, 80]$ ns.



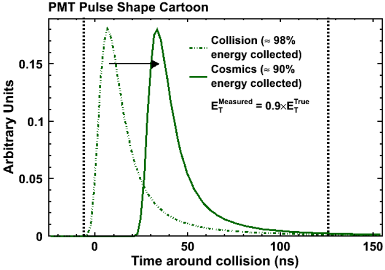
Cosmics DO arrive flat in time, but we now realize that the detector does not measure them perfectly as a function of their arrival time.

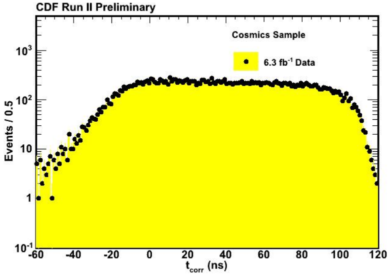
Tower ADMEMs have a 132 ns energy integration window around the collision time. The pulse shape of the PMT has long tails that extend beyond this window, so we collect most of the energy and only need a small correction.

This isn't true for cosmics that arrive later in time. We don't collect all the charge, so this can lead to significant energy under-measurement ($E_T^{measured} \leq E_T^{true}$).

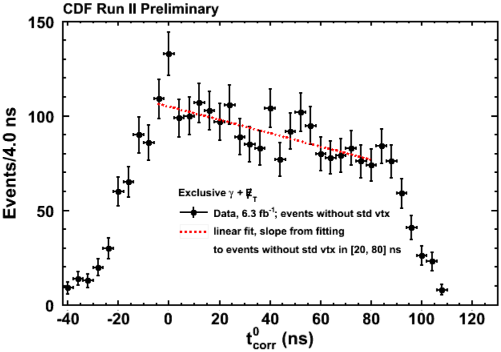
Since the cosmics event rate is a strong function of E_T, shifting the E_T measurement changes threshold cut $\rightarrow$ reduces event rate as a function of time. This causes sharp edges at both sides.

In addition, it also drops slowly for times close to the mean collision time. Hence, cosmics rate drops as a function of Δt





Create very clean cosmics-only sample from data: events which pass all $\gamma + \not{E}_T$ event requirements, but have no vertex (cosmics-enhanced sample) from the data. Data is well-modeled by a simple slope in the region around the signal region (away from energy integration window cut-offs) as expected.



New background estimation method:

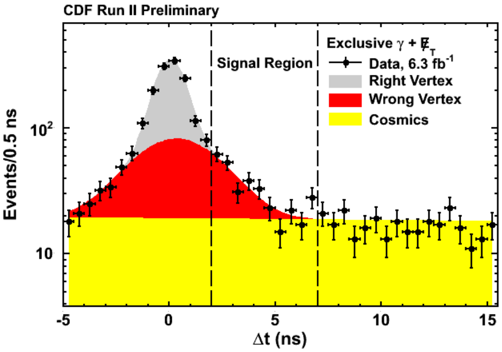
- Use same data, but instead of assuming flat shape, allow cosmics slope and normalization to float
- Increased the background estimate, as well as the uncertainties (still not dominant)
- Slope calculated from fit in the $[20, 80]$ ns region is $= -0.12 \pm 0.03$

Re-run fitter for the $6.3fb^{-1}$ result.

Allow for variation in slope during fitting (the uncertainty goes up), keep the slope in the "No Vertex" and "Good Vertex" samples to be the same. This changes the "WV" background as well. With the 2013 data we get:

Quantity (signal region events)	Prediction (2013)	Prediction (2014)
Events from Cosmics	159 ± 4	187 ± 8
Events from Wrong Vertex	126 ± 24	122 ± 24
Events from Right Vertex	1 ± 1	1 ± 1
Total Expected	286 ± 24	310 ± 24
Observed	322	322

322 on a background of 310 isn't "interesting." This corresponds to 0.4σ. What was once a huge excess (four years ago) is now completely accounted for as the addition of a number of subtle, but important effects that individually contributed a bit:



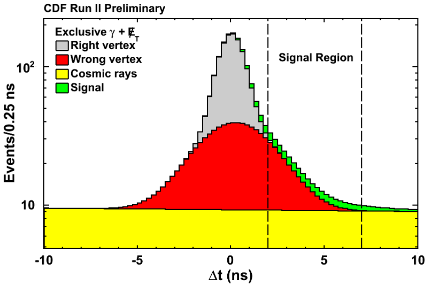
- Biased calibration procedure
- Wrong assumption of $WV_{mean} = 0$
- Poor rejection of $\mathrm{W} \to e\nu$ backgrounds which have biased time
- Poor rejection of large $|Z|$ collisions which have biased time
- Bad cosmics shape prediction

References: CDFNotes 10607, 9924, 10773 & 9812

Limit Setting

Have made significant progress on model-dependent limit setting work based on the results of JHEP 09, 041 (2013)

New particle production usually looks like an exponential in the signal region. Slope depends on model parameters (M_Φ, $M_{\tilde{\chi}_1^0}$ and $\tau_{\tilde{\chi}_1^0}$). Can set limits as a function of slope which allows limits as a function of model parameters.



This is the topic of the next talk.

Conclusions

Moving forward with the search for new physics in the exclusive $\gamma_{Delayed} + \not{E}_T$ final state:

- Added the rest of the data
- Improving Track and EMTiming calibrations on the whole data together
- Improved Cosmics background estimation
- Acceptance model and limit setting in progress
- Publication plan: Two papers
  1. PRD with full method details, results and "final answer"
  2. PRL with results and "final answer"

BACKUPS

Custom Photon ID

Quantity	Selection Cut
EM cluster E_T^0	1 cluster with $E_T^0 > 30$ GeV
Fiducial	$\lvert X_{\mathrm{CES}}\rvert < 21$ cm and $9 < \lvert Z_{\mathrm{CES}}\rvert < 230$ cm
Hadronic fraction	$\frac{E_{\mathrm{Had}}}{E_{\mathrm{EM}}} < 0.125$ $E_{\mathrm{Had}} > -0.3 + 0.008 \cdot E_{\mathrm{T}}^0$*
Energy isolation	$E^{\mathrm{iso}}_{\mathrm{cone}\ 0.4} < 2.0 + 0.02 \cdot (E_T^0 - 20.0)$
1st CES cluster energy	CES $E > 10$ GeV* CES $E/E > 0.2$*
2nd CES cluster energy (if one exists)	CES $E^{\mathrm{2nd}} < 2.4 + 0.01 \cdot E_T^0$
PMT spike rejection	$A_{\mathrm{PMT}} = \frac{\lvert E_{\mathrm{PMT1}} - E_{\mathrm{PMT2}}\rvert}{E_{\mathrm{PMT1}} + E_{\mathrm{PMT2}}} < 0.6$*
Track Multiplicity	Number of N3D tracks either 0 or 1
Track P_T	If $N3D = 1 \rightarrow P_T < 1.0 + 0.005 \cdot E_T^0$

Table: The photon identification criteria. Note that these are standard requirements for high E_T photons, with the following exceptions (marked with a * on the above table): the standard χ^2_{CES} cut is removed, we add a PMT asymmetry cut to reject PMT spikes, and three new cuts on E_{Had}, CES E and CES E/E, are added to reject cosmics.

Cosmics Veto

Quantity	Selection Cut
Muon stub veto	$\Delta(\phi_{textstub} - \phi_{\gamma}) < 30^{\circ}$
Hadronic energy deposited (E_{Had})	$\geq -0.30 + 0.008 \cdot E_T^0$
Total energy in the CES	CES $E \geq 10$ GeV CES $E/E \geq 0.2$

Table: Summary of requirements used to veto photon candidates as originating from cosmic rays. Note, the hadronic energy cut and CES energy cuts are included in the photon ID variable. We include them here in order to explain why these non-standard cuts are present in the photon ID used in this analysis.

Beam Halo Rejection

Quantity	Selection Cut
Number of towers with $E_T^0 > 0.1$ GeV in the same wedge as the photon	> 8
Number of plug hadronic towers with $E_T^0 > 0.1$ GeV	≥ 2

Table: Summary of requirements used to veto photon candidates as originating from beam halo.